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A review of available methods for the alignment of mirror facets of solar concentrator in solar thermal power system ☆

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ABSTRACT

In the concentrated solar power system, the mirror facets of the solar concentrator have to be aligned correctly in order to obtain an optimally focused solar flux at the receiver. In mirror assembly, therefore, it is necessary to develop an accurate, inexpensive and fast measurement method to facilitate the installation and operation of the solar concentrator. In this paper, the available methods for the mirror facet alignment are reviewed. Three kinds of methods including on-sun single mirror facet alignment, mechanical alignment and optical alignment are reviewed in detail. The advantages and disadvantages of these methods are analyzed and discussed. Finally, some future developments are considered.

Contents

1. Introduction

The concentrated solar power (CSP) technology is playing an important role in the expansion of renewable energy applications [1–4]. This technology encompasses four main technologies: the power tower, the parabolic trough, the dish/Stirling, the linear Fresnel. The beam-down is also gaining recognition. In the CSP system, the solar radiation is firstly focused by the concentrator onto the receiver. Circulating fluid in the receiver is heated to provide conventional thermal power generation. The solar concentrator occupies 30–50% of the total cost [5] of the CSP system and its optical performance greatly affects its efficiency. In order to obtain the maximum concentrated solar flux on the receiver, the mirror facets of the concentrator have to be aligned precisely. The mirror facets need to be aligned in orienting (normal direction)

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the mirror surface and in some cases also involves properly shaping (vector height) the mirror. The normal direction alignment of the mirror facets is more important due to the larger influence of the normal direction on the solar flux concentrated on the receiver. The normal direction of a mirror facet can be aligned by canting the mirror surface.

With the development of the CSP, many available methods for the mirror facets alignment have been proposed. In the late1970s, Oldham developed a collimated laser beam method to align the heliostats in a 5 MW Solar Thermal Test Facility [6]. The mirror facets were aligned by reflecting a 1.2 m wide collimated laser beam off from each facet to a specific position on the tower. This method is accurate but very time consuming. In addition, the alignment equipment is huge. About one decade later, Wood developed a distant observer technology to align a parabolic trough concentrator with much more compact equipment [7]. For this technology, the observer can see the Heat Collector Element (HCE) black color completely filling the mirrors, when the concentrator is pointing straight at the observer, the mirrors and HCE are perfectly aligned. This method permits rapid alignment of the mirrors, but the calculated distance needs to be long enough so that it is effectively infinity for the concentrator. Therefore, the above method has its own shortcoming. In 1995, Diver proposed specific requirements for the mirror facet alignment method. These requirements include: (1) the method should be easy to setup and implement; (2) the method has minimum requirement on the sophisticated hardware; (3) the method allows the accessibility to the mirrors for adjustment without needing to remove the receiver and without requiring an absence of sunshine. In addition, there are normally thousands of concentrators in a CSP system and each concentrator has a large size and many mirror facets in general. Therefore, a fast measurement method for the mirror facet alignment in the installation and operation of the solar concentrator field is needed.

Many methods have been put forward and applied in the past 30 years. These methods can be divided into three main kinds based on the alignment characteristics. The first kind is the on-sun single mirror facet alignment method. The second kind is the mechanical alignment method by using gauge blocks or inclinometers. The third technique is the optical alignment method based on image processing and photographic techniques. In this paper, these three kinds of the mirror facet alignment methods are presented. The advantages and disadvantages of these methods are analyzed and discussed in detail. And finally, the outlook for this evolutionary technology is examined.

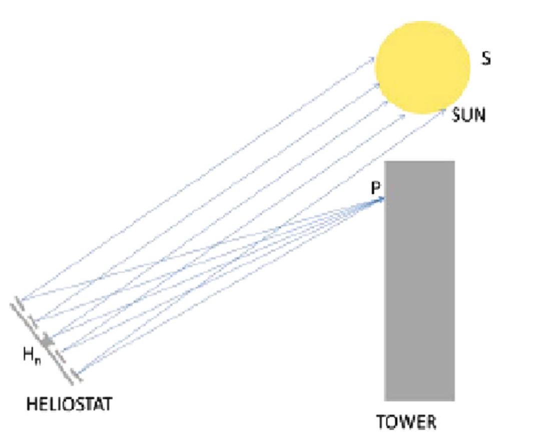


Fig. 1. Schematic of the on-sun single facet alignment method [9].

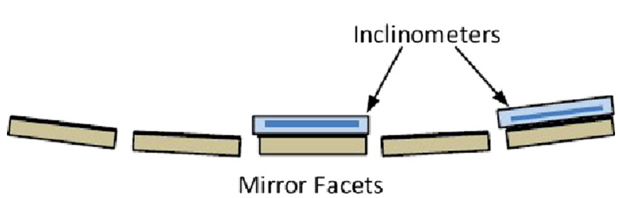


Fig. 2. A schematic of the inclinometers method to cant the mirror facets [13].

2. Techniques for the mirror facet alignment

2.1. On-sun single mirror facet alignment method

The on-sun single mirror facet alignment method was widely used in CSP systems in the early years of development [8–12]. In this method, the position of the sun is assumed unchanging during the alignment process of the solar concentrator. The central mirror facet is aligned first, and then the remaining mirror facets are aligned sequentially. One can assess the positional displacement of any facet by comparing the observed beam 'spot' at the receiver with the predicted 'spot' for an ideal concentrator. In the 1970s, the NSTTF began to use this method to align the heliostats [8]. A schematic of this method is shown in Fig. 1.

In order to implement the above technique, it is not necessary to know the surface shape of the solar concentrator. The alignment is easy and relatively inexpensive. However, this method can only be used on an already installed CSP system, and only during periods of good sunshine. Moreover, when the chosen mirror facet is being aligned, the remaining already focused facets have to be covered to prevent their light spots from hindering adjustments on the facet of interest. Therefore, although this method is qualitatively simple, it is more time consuming and less accurate than some alternatives.

2.2. Mechanical alignment methods

The heliostats employed in the power tower system have the longest focal length of currently available solar concentrators. It usually consists of an array of rectangular mirror facets which have small curvature. The mirror surfaces can generally be regarded as flat surfaces. In this case, the heliostats can be aligned in the factory by employing the mechanical methods outlined below.

During early development of the power tower system, the gauge block method was used to set the mirror facet angles [13]. The position of the heliostat with respect to the tower in the center of the heliostat field needs to be known in order to determine the canting angle of each mirror facet. The heliostat is positioned horizontally during the alignment process. The reference plane can be defined by calculation, and hence the gauge blocks can be made for aligning the mirror facet. The specified gauge block is then used to set up the 'ideal' position of the mirror facet to as high accuracy as the manufacturing process allows.

Considering that the gauge blocks method requires a very large number of blocks, an improvement called the inclinometers method has been evolved and applied by the NSTTF [9,13]. Before aligning the mirror facets, the theoretical tilt angles of the mirror facets are calculated according to the position of the heliostat. The face of the heliostat is inclined upwards when aligning the mirror facet. Since the inclinometer in question can only measure one angle accurately, the vertical tilt of the mirror facet and the horizontal tilt angle must be measured separately. A schematic of the inclinometers method used to determine the cant of the mirror facets is shown in Fig. 2.

Other inclinometer mechanical methods employing linear displacement transducers have been implemented at Solar One station [9,10]. This method uses a transit made of a bubble-leveled rod to provide the reference plane for displacement measurement.

An inclinometer can also be used at the mirror facet center to implement the correct tilt.

When a heliostat field is built, the position of each mirror facet can change with the effect of gravity, therefore the above two methods may lose accuracy. They can also be very time consuming although in the heliostat case the position is calculated in advance. The inclinometers method has an accuracy of up to 1.5 mrad and is more accurate than the use of gauge blocks. In addition, it is easy and very cost-effective. However, as the inclinometers are required to make contact with the mirror facets during alignment potentially harmful contamination of the mirror surface can occur. In general, the inclinometers method is a good option for those heliostats exhibiting a small number of mirror facets.

2.3. Optical alignment methods

2.3.1. Laser method

The inclinometers method presents cumbersome alignment issues in setting up the mirror facets of a heliostat. These are overcome by the scanning prism laser projection method, a new concept proposed by SNL [13]. This system consists of a laser, a beam splitter, number of prisms, and a position sensing detector (PSD). A schematic of this method is shown in Fig. 3. The measurement process is as follows: the laser beam firstly impinges on a beam splitter and is deflected to incident onto the mirror facet. It then passes through a number of prisms before it is finally focused onto the PSD. The tilting angles of a chosen mirror facet can be obtained by comparing the actual spot position with the ideal spot position at the PSD. Two tilting angles in directions of all mirror facets can be calculated by referring to the angle of the center of the mirror facet. The misalignment of the mirror facet can be adjusted according to the output tilting angles of PSD. The aligning process is repeated carefully until the ideal tilting angle is achieved.

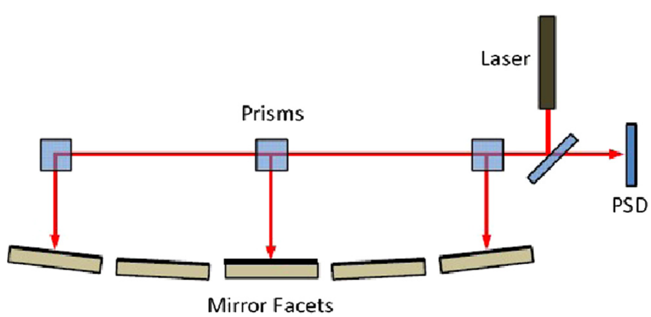


Fig. 3. A schematic of the scanning prism laser projection [13].

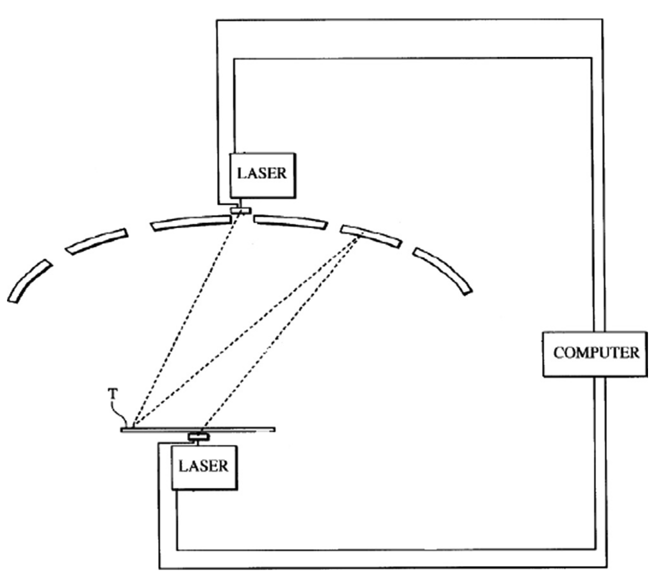


Fig. 4. Schematic of the two-laser method [14].

In 2003, Diver developed a new method which uses two lasers based on the conventional laser technique. This method is used to align the mirror facets of a trough concentrator [14]. The first laser is approximately positioned at the focal length location. The laser beam transmitted by the first laser is incident onto a chosen mirror facet of the concentrator, and then the beam is reflected onto the fixed target. The target is positioned at the adjacent position of the first laser. The color of the second laser beam is different from the first laser, and it is located at an adjacent position to the vertex of the optical axis of the solar concentrator. The second laser beam hits the theoretical position of the target. The precise alignment is achieved by adjusting the chosen mirror facet so that the first laser beam spot falls exactly on the target point on the target board produced by the second laser beam. The schematic of the two-laser method is shown in Fig. 4.

Evidently, the laser method is a non-contact method and hence the contamination of the solar concentrator can be effectively avoided. Of course, both methods mentioned above have their own advantages and disadvantages. The scanning prism laser projection method can give the deviation of the mirror facet in terms of two tilting angles accurately on day and night. The alignment time taken by the scanning prism laser projection method is far less than that of the mechanical method. However, the alignment tool will be huge when the size of the heliostat is quite large. The advantage of the two-laser method is that it permits multiple sample points on a mirror facet to be taken so that the effect of the local slope error can be eliminated. The shortcoming is that it requires knowledge of the exact position of the trough concentrator and the aim point coordinates in advance for the proper setting of the target. Considering the advantages and disadvantages of both methods, they are more suitable for use in the factory.

2.3.2. Camera look-back

The camera look-back method has been successfully used to align heliostat mirror facets at the NSTTF [13,15]. This method is an on-axis alignment method and the shape of the heliostat surface must be approximately parabolic. When the camera is positioned at the heliostat focal position, the camera 'sees' its reflected image in the mirror facet. The camera is positioned atop the receiver

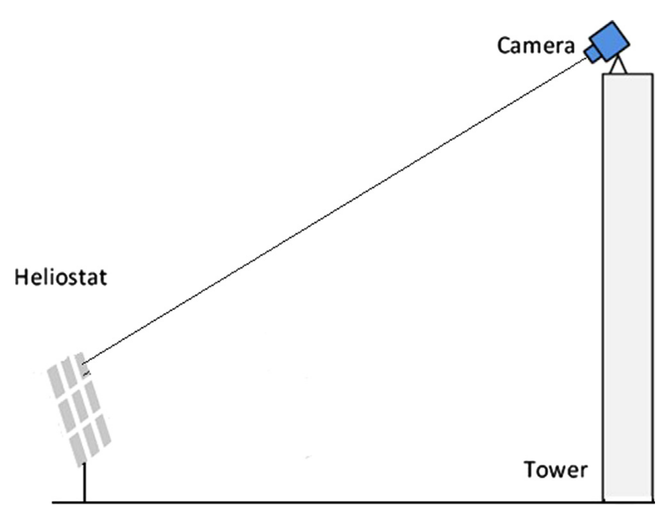


Fig. 5. A schematic of the camera look-back method.

tower (Fig. 5). The normal direction vector to the central mirror facet can align to be coincident with the optical axis of the camera by adjusting the azimuth and elevation angles of the heliostat. This position of the heliostat is regarded as the reference position. The theoretical direction normal of other mirror facets can be calculated by referring the reference position. The heliostat is adjusted in azimuth and elevation directions until the normal direction of the chosen mirror facet points at the center of the camera lens. The chosen mirror facet is aligned until the reflected image of the camera falls onto the center of the field-of-view of the camera.

In the process of alignment, the heliostat needs to be adjusted repeatedly so that this process is again very time consuming. The alignment accuracy greatly depends on the precision of the camera algorithm as well as the heliostat tracking error. It has still been demonstrated to be acceptably accurate even when using only one camera.

2.3.3. *Photogrammetry*

The photogrammetry procedure is a quantitative analysis tool designed to determine the surface shape of the solar concentrator from photographs [16]. In 1996, this method was employed by Shortis et al. to analyze the surface shape of the so called “Big Dish” with an area of 400 m^2 at the Australian National University [17–19]. In this method, a number of marks are firstly pasted on the surface of the solar concentrator and then two or more cameras are used to take photographs of the solar concentrator from different view angles. Since the relative positions of these photographic images are connected to the corresponding marks on the solar concentrator surface, one can calculate the coordinates of these marks based on the collinearity principle and then the concentrator surface shape can be fitted.



Fig. 6. Frame of a Euro Trough module with measurement targets on the support points [20].

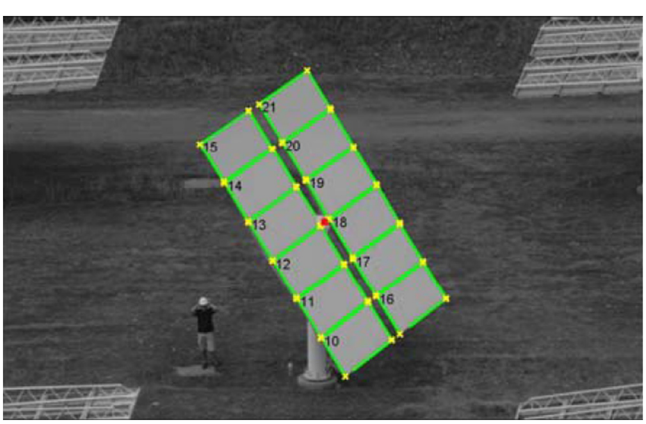


Fig. 7. A schematic of edge detection method [21].

While the conventional photogrammetry, as described above, can be used to measure the surface shape of the solar concentrator, the tilting angles of all mirror facets cannot be measured by this method directly. In 2005, Pottler et al. proposed the digital close-range photogrammetry method to measure the structural shape of the solar concentrators [20]. The retroreflective marks are placed on the mirror facet support points and the images are recorded by the cameras from different view angles. The coordinates of all marks can be calculated by analyzing the images. The height deviation can be obtained by comparing the actual position with the theoretical position at each supporting point. The solar concentrator can be well aligned by correcting the height deviation repeatedly during the aligning process. Fig. 6 shows the frame of the Euro Trough module in its zenithal.

Above photogrammetric methods are very time-consuming because the marks need to be preset and the coordinates of the marks need to be extracted through complex calculations. To address this issue, a new photogrammetric method based on edge detection has been proposed by Marc Röger et al. in 2008. This method takes advantage of an aspect of most heliostats namely that they normally have a regular structure and are usually composed of many rectangular mirror facets [20,21]. In that the normal direction vector of the mirror facet can be calculated according to the coordinates of the four corners of the facet, therefore one only needs to determine the coordinates of these corners by combining several image processing techniques. The alignment process includes four steps. These are: image acquisition, image processing, normal vector calculation and adjustment. The images of the heliostats can be recorded by a digital camera located atop the tower. In this method, 20 images of the same heliostat are recorded so that a sound statistical characterization is reached. The position of the heliostat in the picture is modified by moving the camera slightly. Since four corners of the mirror facet are detected automatically in this method, the alignment time can be reduced significantly. This method was successfully used to align a 40-m^2 CESA-1 heliostat at the Plataforma Solar de Almerìa. A schematic of the edge detection method is shown in Fig. 7.

The photogrammetry can achieve the solar concentrator alignment with a standard deviation of less than 0.2 mm. The edge detection photogrammetry can calculate the heliostat orientation and the normal direction of the mirror facet. Heliostat orientation is available within 3 min, and the measurement uncertainty of the position is less than 4 mrad for more than 80% of the relevant heliostat positions. The accuracy of the normal direction of the mirror facet is 1.6 mrad with the results being available within 30 min [21]. As manufacturing technology develops and improves, the error of the mirror facet dimension will be controlled to under ± 1 mm. In summary, this method is sufficient to detect the misalignment of the mirror facet in existing heliostat fields economically.

2.3.4. *Fringe reflection or deflectometry*

Deflectometry is an optical measurement technique originating in the car manufacturing industry, and it is virtually identical to the “Fringe Reflection Technique” developed by BIAS [22–25]. It is a projection-based technique. In this technique, a fringe pattern is projected onto a screen which is then reflected by a mirror, and finally the reflected image is recorded by a digital camera. The distortion of the mirror surface is calculated based on the distortion of the fringe image. Horneber et al. have developed the technique further in order to establish an improved method called “Phase Measuring Deflectometry” (PMD) [24,26]. In this method, a sinusoidal pattern is generated on the screen by a projector, and then four successive images of the mirror corresponding to the patterns with a phase shift difference of $\pi/2$. These are captured by

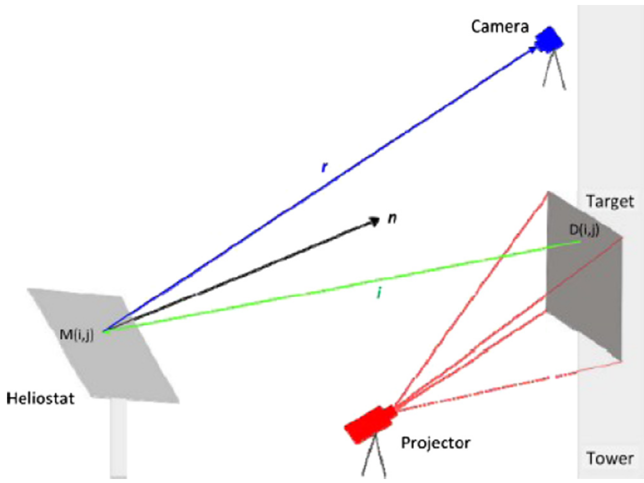


Fig. 8. A schematic of the fringe reflection method of aligning a heliostat [27].

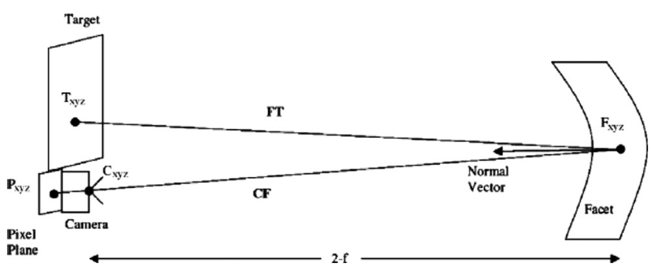


Fig. 9. Schematic of the SOFAST method [29].

a digital camera. Once the images with different phase shifts are acquired, the slope perpendicular to the fringe direction can then be calculated by the phase shift algorithm directly.

A method based on PMD applied to heliostat alignment has been proposed by Ulme in 2010 [27]. A schematic of the fringe reflection method is shown in Fig. 8. The measurement system consists of a projector, a high resolution CCD camera and a large diffuse emission screen on the tower. The projector is located on the ground to generate a series of sinusoidal patterns on the screen. The camera accepts the fringes reflected by the heliostat. After pre-measurement calibration, the slope which is perpendicular to the fringe direction can be computed by using the four phase shift algorithm.

In the fringe reflection method, every pixel of the camera can be precisely mapped to the heliostat as well as to the screen. Every pixel of the camera corresponds to a light ray which intersects a point on the heliostat, and the corresponding coordinate of the point can be computed on the screen by using the law of reflection [13,28]. The specific normal direction vector of each point can be calculated by the incident and reflected rays. The deviation from the normal direction of the heliostat surface can be obtained by comparing it with the normal information of the ideal heliostat. According to the normal error information, the misalignments of the mirror facets can be precisely corrected. At present, a measurement uncertainty of less than 0.2 mrad can be achieved by tracing a sum of about 1 million points per heliostat [27]. The tilting angles of each mirror facet can be obtained by averaging the local slope errors of the heliostat surface. The calculated tilting angle has a limited resolution of only about 1 min for a heliostat. A disadvantage of this alignment method is that it is only able to function at night.

In 2011, Andraka et al. reported the practical application of the fringe analysis slope technique (AIMFAST) on an alignment implementation in the manufacturing factory initially based on

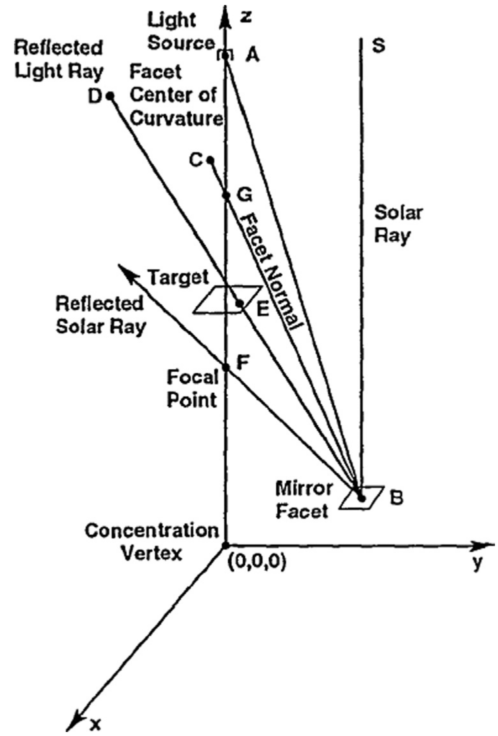


Fig. 10. The principle of the theoretical overlay method [31].

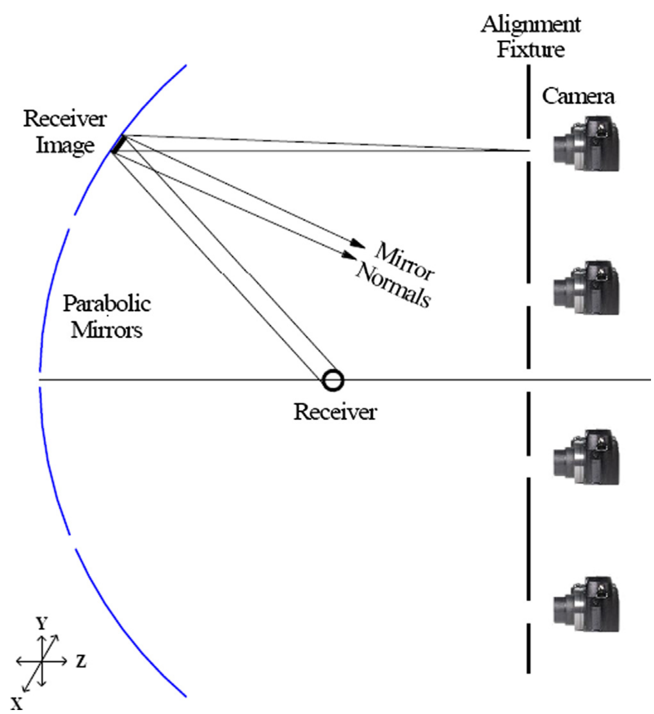


Fig. 11. The schematic of the TOPCAT method [32].

SOFAST [29]. It had been implemented on a dish concentrator prototype. A schematic of the SOFAST system is shown in Fig. 9. A LCD screen is used as a target to generate a series of sinusoidal fringe patterns, and a camera located at near the 2f location of a dish concentrator is used to record the reflected images from the dish concentrator. Like the other fringe reflection method, the normal vector of the concentrator surface can be calculated based on the reflection principle. The deviation angle of the facet can be obtained by averaging the local normal errors of the chosen mirror

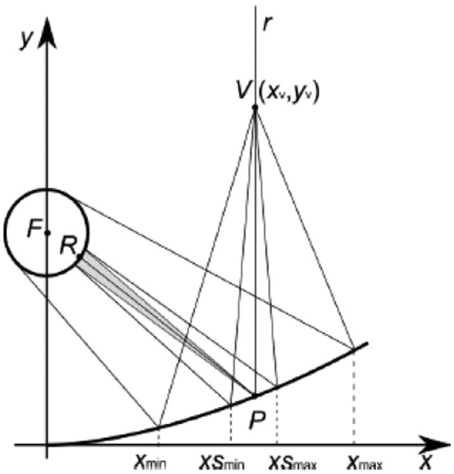


Fig. 12. Reflected image of receiver observed from the view point V [34].



Fig. 13. Measurement set-up of the theoretical image overlay technique in the field [35].

facet. This method has been proposed to support the alignment of the so called SunCatcher dish/Stiring system, and the alignment error of the dish concentrator is under 0.25 mrad.

2.3.5. *Theoretical image overlay method*

In 1995, Diver first proposed a theoretical image Overlay method to align the mirror facets of CPG-460 solar concentrator in dish/Stiring systems [30]. In this method, a beam of light from an artificial source is reflected to the target through the mirror facet. From basic geometric principles, one can calculate the 'spot' shape and the location of the reflected light that falls on the target. The reflected image falls on the predetermined location by aligning the chosen mirror facet repeatedly. Fig. 10 shows the principle of the theoretical overlay method.

The Theoretical Overlay Photographic Collector Alignment Technique (TOPCAT) is a new technique that is derived from the accurate parabolic dish alignment method [30–33]. This procedure is mainly used for trough concentrator alignment. Fig. 11 shows the schematic of the TOPCAT method. The theoretical location of the image of HCE edges in the mirror facet can be calculated. Four digital cameras capture the images of the four rows in a trough concentrator, and then the position deviation of the mirror facets can be calculated by comparing the theoretical HCE position with actual position in the image. The alignment fixture is placed at a convenient distance from the trough concentrator. This distance is close enough to be within the rows of reflectors in a power plant, but a camera can still 'see' a concentrator which has 20 mirrors in an LS-3 collector located far away. In the alignment process, the trough concentrator is horizontally directed and the alignment fixture is positioned vertically. It was demonstrated that a 3.5% increase in thermal performance of an LS-3 loop can be achieved by this method. The alignment fixture is an extremely cost effective tool and the alignment time is rather short.

Unfortunately the TOPCAT method does not allow one to measure the intercept factor (IF) in order to evaluate the alignment test. In order to address this issue, a new instrument, named Visual Inspection System Field (VISfield), has been developed by MARPOSS in cooperation with others [34], and is shown in Fig. 12. In this method, a hypothetical spot of solar radiation that is assumed to be reflected by P will appear from an observer at V as a spread in the receiver image between $XS_{\min}$ and $XS_{\max}$. The local IF is given by the portion superimposing on the receiver image. In order to get an average IF for a global module and for single panels, this analysis process has to be repeated from different observation points. It only uses one camera to scan from the vertex to the outer parabola border in the y direction. After the facet mirrors are properly aligned, the facet compliance can be rechecked.

Since the theoretical image overlay technique has been successfully demonstrated for aligning the trough concentrators, a new concept based on this method in heliostat alignment has been proposed in recent years [33,35]. In the new method, the alignment fixture has five cameras and nine special targets. These cameras are deployed in two dimensions. One camera is located in the center and others are located in the four corners. The size of the alignment fixture is equivalent to the chosen heliostat. At the beginning of the process, the alignment fixture is placed in front of the heliostat and it is oriented vertically. Each camera is used to take many pictures corresponding to six adjacent mirror facets. Based on rangefinder, one can determine the relationship of the distance between the alignment fixture and the chosen heliostat. The theoretical position of the nine targets can be calculated from the image based on reflection principles. The mirror facet is aligned repeatedly until the photographic images of the targets match the theoretical images. The set-up in the field is shown in Fig. 13.

In the theoretical image overlay method, the solar concentrator can be aligned by comparing the actual position and their predicted theoretical position in the image. This method is an accurate and effective method to improve the collection efficiency of the concentrator. In addition, the VISfield based on this method can also be used to check the shape quality of each facet mirror especially. It can be used during the assembly phase of concentrator or in the field during the installation phase in day time.

2.3.6. *Target reflection method*

The target reflection method is a new method used for the heliostat alignment. This method has been proposed by Sandia National Laboratories (SNL) and New Mexico Tech (NMT) in recent years [36,37]. This method uses a high resolution digital camera to view the reflection image of a target generated by the heliostat. The digital camera with a zoom lens is mounted atop the central tower. The target with colored fabric stripes can be placed at any distance from a heliostat. For example, the target is designed in a five-by-five cross-hatch pattern in which each of the stripe intersections corresponds to the center of one of the 25 heliostat facets [8]. However, since the heliostat mirrors are not of high quality, features on the target are not easily identified. The target can be placed at any distance in front of the heliostat to improve the image quality. In this method, one can accurately calculate the theoretical position of the stripe intersection through a

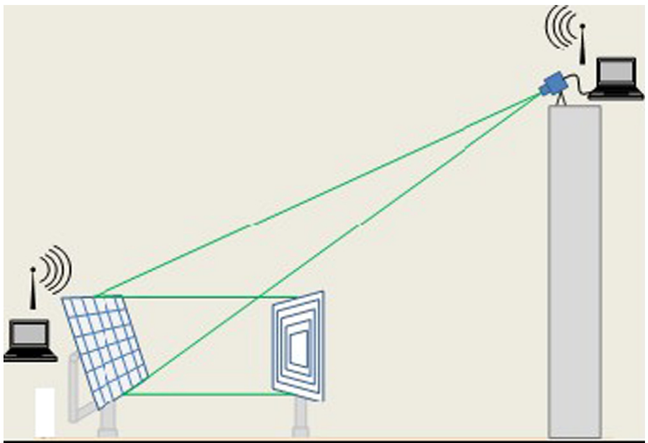


Fig. 14. A schematic of the target reflection method to cant and focus the mirror facets [36].

corresponding mirror facet in the image. The misaligned mirror facets are aligned until the actual image of the target can cover the theoretical image [13]. A schematic of the target reflection method is shown in Fig. 14.

After the alignment, the heliostat is placed on the field and the reflected beam on the receiver is evaluated. The measurement result of the sun disc has shown that this method is feasible. It is also shown that an alignment accuracy of about 0.3 mrad can be achieved. In general, this method is simple, cost-effective, accurate and efficient to realize the alignment between the mirror facets and the heliostat in the heliostat field.

3. Summary and outlook

In this paper, three kinds of methods for the solar concentrator alignment have been reviewed, including on-sun single facet alignment, mechanical alignment and optical alignment. The advantages and disadvantages of these methods have been discussed. For the on-sun single mirror facet alignment method, there is no need to know, in advance, the surface shape of the solar concentrator, and hence all kinds of solar concentrators in CSP can be aligned. This method is therefore easy and inexpensive. However, unused mirror facets must be obscured to prevent light interference with the reflection spot on the receiver associated with the mirror facet being adjusted. This makes this method more time-consuming and less accurate.

Mechanical alignment method mainly includes the gauge block method, the use of inclinometers and the linear displacement transducer method. These methods are used to align heliostats which have many flat mirror facets. The gauge block method is more time-consuming and less accurate although the position of every mirror facet is recalculated. The inclinometers method can significantly improve the alignment accuracy and can exhibit 1.5 mrad in the factory. The linear displacement transducer method is relatively faster in comparison with the inclinometers method. In general, the mechanical alignment method is not suitable for large-scale heliostat field, but it is simple and effective for a heliostat system which has a small number of mirror facets.

Optical alignment mainly includes the laser method, the camera look-back method, the photogrammetry, the fringe reflection method, the theoretical image overlay method and the target reflection method. The optical alignment method can offer a higher alignment efficiency and accuracy. The fringe reflection method is the fastest to implement and the most accurate in the factory or in the solar concentrator field, but it can only be used at night. Compared to the theoretical image overlay method and the target reflection method, the fringe reflection technique involves complex calibrations and data analysis. The camera look-back method is an optical alignment method which requires the least amount of hardware, but it is more suitable for the parabolic shape heliostat. Other optical methods, such as the laser method, the edge detection photogrammetry, the theoretical image overlay method and the target reflection method, can satisfy the practical needs of heliostat alignment on both day and night. Only the two-laser method, photogrammetry and the theoretical image overlay method are able to align trough concentrators and dish concentrators fast and accurately.

The solar concentrator is the key component of any CSP system. To develop an accurate, inexpensive and fast method for aligning these devices is very important. Considering the characteristics of the available methods, it can be concluded that the fringe reflection method is used to align heliostat in a factory, the target reflection method is perfectly suitable for the heliostat alignment in the field, and the theoretical image overlay method is more suitable for the parabolic trough and dish concentrator in the field.

Acknowledgments

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